SURFACE WAVE INSPECTION OF POROUS CERAMICS AND ROCKS

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INTRODUCTION

The most interesting feature of acoustic wave propagation in fluid-saturated porous media is the appearance of a second compressional wave, the so-called slow compressional wave, in addition to the conventional P (or fast) wave and the shear wave [1,2]. The slow compressional wave is essentially the motion of the fluid along the tortuous paths in the porous frame. This motion is strongly affected by viscous coupling between the fluid and the solid. Therefore, both the velocity and the attenuation of the slow wave greatly depend on the dynamic permeability of the porous frame. It was not until 1980, that Plona first experimentally observed the slow compressional wave in water-saturated porous ceramics at ultrasonic frequencies [3]. Only three years later, Feng and Johnson predicted the existence of a new slow surface mode on a fluid/fluid-saturated solid interface in addition to the well-known leaky-Rayleigh and true Stoneley modes [4,5]. The slow surface mode is basically the interface wave equivalent of the slow bulk mode, but there is a catch: the surface pores of the solid have to be closed so that this new mode can be observed. Otherwise, a surface vibration can propagate along the fluid/fluid-saturated porous solid interface without really moving the fluid since it can flow through the open pores without producing any significant reaction force. All previous efforts directed at the experimental observation of this new surface mode failed because of the extreme difficulty of closing the surface pores without closing all the pores close to the surface (e. g., by painting). On the other hand, it has been recently shown that surface tension itself could be sufficient to produce essentially closed-pore boundary conditions at the interface between a porous solid saturated with a wetting fluid, such as water or alcohol, and a non-wetting superstrate fluid, like air [6]. Capillary forces extend an ideally thin membrane over the surface pores at the boundary with the non-wetting fluid. This membrane is usually so stiff that it assures "closed-pore" boundary conditions at the interface. Owing to this simple effect, the slow surface mode can be observed in porous ceramics as well as in natural rocks of high permeability. We are going to show that the velocity and attenuation of the slow surface mode can be used to assess the dynamic permeability of the porous formation.

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Feng and Johnson showed that four boundary conditions have to be satisfied at the fluid/fluid-saturated porous solid interface: (i) the continuity of the normal stress, (ii) the diminishing nature of the transverse stress, (iii) the conservation of fluid volume, and (iv) Darcy's law which claims that there is a proportionality between the discontinuity in the fluid pressure and the relative fluid displacement at the interface:

$$p_f(z=0^-) - p_f'(z=0^+) = T\phi(U_z - u_z), \quad (1)$$

where p_f and p_f' denote the pressure in the substrate and superstrate fluids, respectively. u_z and U_z are the displacements of the solid and the fluid, respectively, ϕ is the porosity and T denotes the surface stiffness.

The analytical method of Feng and Johnson [4,5] can be easily applied to a surface wave propagating along the "free" (air-loaded) surface of a fluid-saturated rock. In the ideal case of completely closed surface pores and viscosity-free fluid, two types of surface wave can propagate: there is a pseudo-Rayleigh mode, which leaks its energy into the slow compressional wave, and a true surface mode with velocity slightly below that of the slow wave. The second mode is a simple form of the new interface mode predicted by Feng and Johnson when the superstrate fluid is extremely rare and highly compressible like air. Theoretically, the slow interface mode becomes slightly leaky, too, since its velocity is higher than the sound velocity in air, although the actual energy loss is negligible because of the large density difference between the two fluids.

A detailed description of the boundary conditions and the derivation of the characteristic equation can be found in Ref. 4. Table I lists the different bulk and surface wave velocities calculated for dry (air-saturated) and wet (alcohol-saturated) porous glass by neglecting viscosity.The following parameters were used in these calculations (with the notation of Ref. 4): $\rho_f = 7.9\ 10^2$ kg/m^3, $\rho_f' = 1.3$ kg/m^3, $\rho_s = 2.48\ 10^3$ kg/m^3, $K_f = 1.03\ 10^9$ N/m^2, $K_f' = 1.5\ 10^5$ N/m^2, $K_s = 4.99\ 10^{10}$ N/m^2, $K_b = 5.66\ 10^9$, $N = 3.15\ 10^9$ N/m^2, $\phi = 0.3$, $\alpha_\infty = 1.79$. Methyl alcohol was used to saturate the porous material since the sintered glass sample happens to be somewhat hydrophobic. Also, the sound velocity in alcohol is 20% lower than in water, therefore the effect to be demonstrated is much stronger in the case of alcohol saturation. The tortuosity was taken to be 1.79, which gives the best agreement between experimental measurements and theoretical predictions for the

Table I Calculated sound velocities in dry and wet porous glass.

	dry	wet
fast wave	2,383 m/s	2,529 m/s
slow wave	254 m/s	766 m/s
shear wave	1,346 m/s	1,308 m/s
surface wave		
- open pores	1,242 m/s[a]	1,209 m/s[b]
- closed pores	1,241 m/s[a]	745 m/s[c]

[a]Rayleigh mode [b]pseudo-Rayleigh mode [c]slow surface mode

bulk slow wave velocity in this type of porous glass [7]. On the dry sample, the surface wave velocity is approximately 8% lower than the shear wave velocity, regardless whether the surface pores are open or closed. On the wet sample, the surface wave velocity is very sensitive to the boundary conditions. For open pores, the surface wave velocity is again approximately 8% lower than the shear velocity, although both velocities are somewhat lower than in the dry sample due to the added inertia of the saturating fluid. On the other hand, for closed pores, the velocity of the true surface wave becomes as much as 40% lower than the shear velocity when the sample is wet.

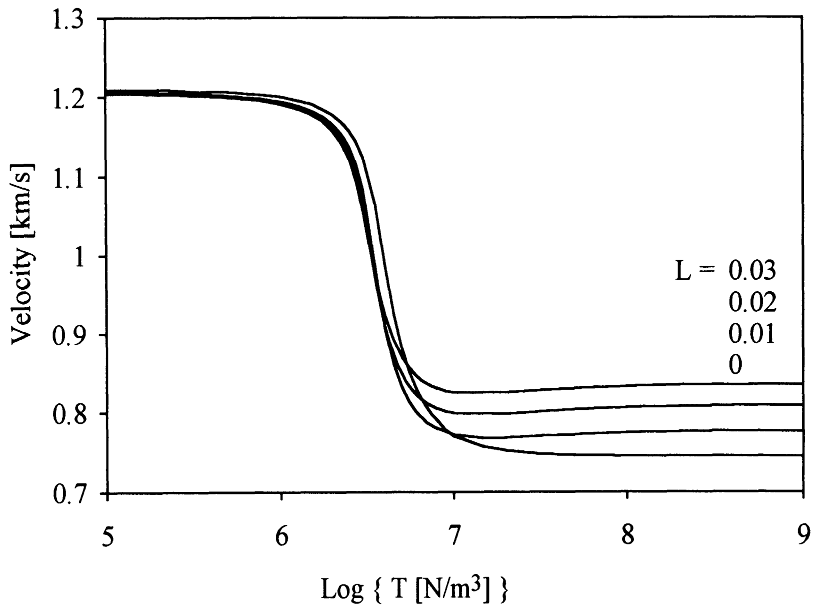

Fig. 1. Surface wave velocity versus surface stiffness on the "free" surface of alcohol-saturated porous glass for different loss factors.

Feng and Johnson considered completely open (T = 0) or closed ($T = \infty$) surface pores only and assumed viscosity-free flow of the fluid through the pore channels. We extended these calculations to the more general case of arbitrary surface stiffness. Furthermore, in order to account for viscous losses in the fluid at finite frequencies, we introduced a complex tortuosity in the form of [8] $\alpha(\omega) = \alpha_\infty[1+(iL)^{1/2}]$, where α_∞ is the real-valued geometrical tortuosity, L denotes the viscous loss factor, and ω is the angular frequency. Figure 1 shows the calculated velocity of the slow surface wave propagating on the surface of alcohol-saturated porous glass as a function of the surface stiffness. The velocity drops from 1,209 m/s to 745 m/s as the surface stiffness increases. There is a fairly sharp turning point around 10^7 N/m^3. This is in good agreement with previous predictions for the transition range between open- and closed-pore boundary conditions [9]. Figure 1 also shows how the surface wave velocity slightly increases when viscous losses are taken into account. Since the phase velocity of the bulk slow wave decreases with increasing viscous loss, the slow surface wave becomes leaky into the substrate, too.

We are going to show that capillary forces can extend an ideally thin membrane over the surface pores at the boundary with the non-wetting fluid, which is usually so stiff that it assures closed-pore boundary conditions at the surface. For the sake of simplicity, let us assume that the pores are cylindrical holes of radius a (see Fig.2). Although there is usually a thin layer of liquid wetting the entire surface of the sample, the thickness of this layer is so small that viscosity keeps the fluid in it immobile. According to the Laplace law, the radius of the surface membrane is

$$R = \frac{2\sigma}{p_0 - dp}, \tag{2}$$

where σ denotes the surface tension, p_0 is the hydrostatic pressure, and dp is the acoustic pressure. Assuming that the meniscus is co-planar with the surface of the sample, the acoustic pressure changes the fluid volume in the pore by

$$dV = dR\,\frac{a^4\pi}{4R^2} = dp\,\frac{a^4\pi}{8\sigma}. \tag{3}$$

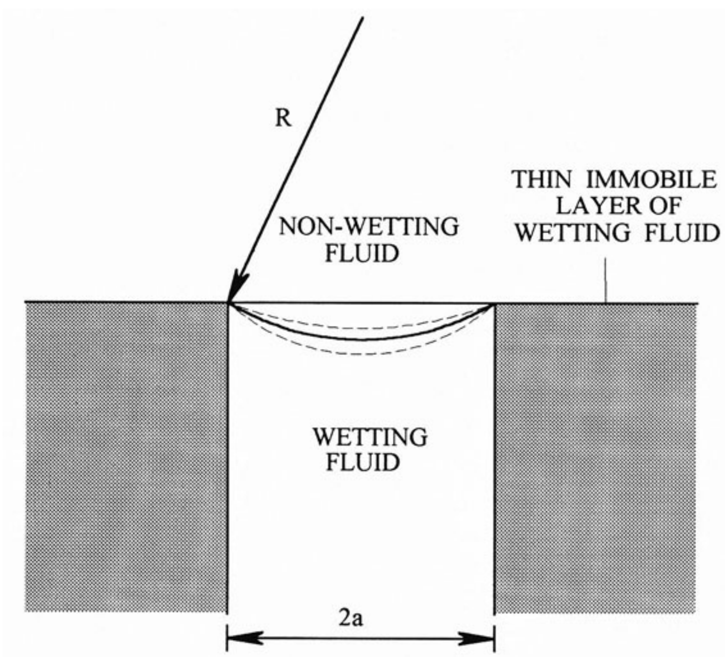

Fig. 2. Boundary curvature due to surface tension.

The relative fluid displacement with respect to the solid frame is:

$$U_z - u_z = \frac{dV}{a^2 \pi} = dp \frac{a^2}{8\sigma} \ . \tag{4}$$

From Eqs. 1 and 4, the effective surface stiffness can be written as follows:

$$T = \frac{8\,\sigma}{\phi\, a^2} \ . \tag{5}$$

According to Darcy's and Poiseuille's laws, the static permeability of a porous solid containing cylindrical pores is:

$$\kappa_o = \frac{\phi\, a^2}{8} \ , \tag{6}$$

so that Eq. 5 simplifies to $T \approx \sigma/\kappa_o$. For methyl alcohol in contact with air, $\sigma = 2.3\ 10^{-2}$ N/m, and even a relatively high static permeability of $\kappa_o = 10$ Darcy $\approx 10^{-11}$ m^2 produces a surface stiffness in excess of 10^9 N/m^3. A quick comparison with Fig.1 verifies that, for all practical purposes, the surface pores are sealed under these conditions.

EXPERIMENTAL SYSTEM AND RESULTS

Figure 3 shows the schematic diagram of the experimental arrangement used in this study. The surface mode was excited by a vertically polarized shear transducer mounted at the edge of the specimen. The transmitter was driven by a tone-burst of three cycles at 100 KHz. Two detection techniques were used. On alcohol-saturated ceramics, the normal component of the surface vibration was measured by a laser interferometer at two locations separated by 10 mm along the propagation direction. At both axial positions, the laser beam was scanned by ±5 mm in the lateral direction so that spatial averaging could be used to improve the accuracy of the measurement. On water-saturated natural rocks, the surface mode was detected by a second vertically polarized shear transducer mounted at the opposite edge of the specimen.

As an example, Fig. 4 shows the surface wave velocity and attenuation coefficient as functions of saturation time. Owing to the low viscosity of methyl alcohol, more or less complete saturation is reached within a few seconds after the bottom of the 1"-thick sample is soaked. As a result, the velocity quickly drops from 1,240 to 1,090 m/s and the attenuation increases by almost a factor of two. At this point, the slow wave propagation is still very weak since some of the pores are clogged by trapped air bubbles. At room temperature and atmospheric pressure, it takes approximately one hour for the alcohol to dissolve the remanent air saturation thereby opening the blocked pore channels. During this period, the surface wave velocity drops to 840 m/s and the attenuation coefficient increases to 1.1 dB/mm. By adjusting the loss factor in our calculations, we can match the analytical results to the experimental data. On the basis of the velocity only, the loss factor is approximately 0.03, which produces 1.7 dB/mm attenuation at 100 KHz, i. e., somewhat higher than the measured value. This slight discrepancy might be due to our overestimation of the stiffness of the surface membrane by neglecting the effect of the wetting fluid

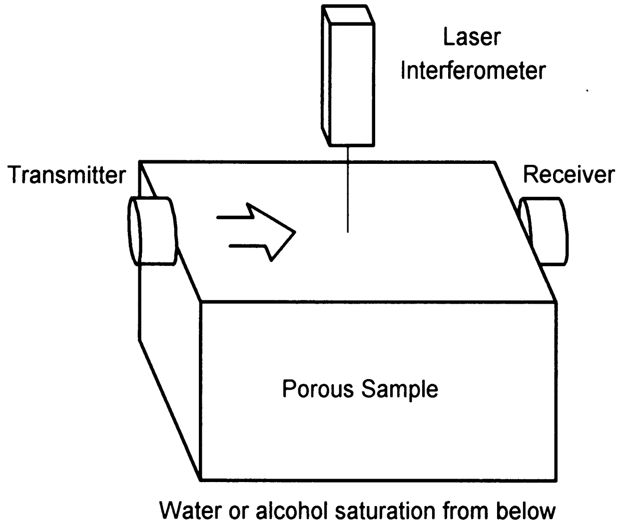

Fig. 3. Experimental arrangement.

covering the surface of the sample and the rather crude approximations used in our analytical model for viscous losses.

One of the main advantages of the slow surface mode, in comparison with the slow bulk mode, is that it can be observed in water-saturated natural rocks, too. Although, similarly to its bulk counterpart, the slow surface mode is greatly attenuated by viscous losses in natural rocks, its detectability is still much better. This is because both competing surface modes, i. e., the Rayleigh and Stoneley modes, are strongly leaky into the very lossy slow bulk mode and are decaying much faster than the slow surface mode. With no other modes propagating on the surface, the slow surface mode can be easily recovered from the dominating electrical noise by extensive averaging in the time domain. Figure 5 shows the measured surface wave velocity in water-saturated Massillon and Berea sandstones between 100 and 600 mD. In natural rocks, as long as two-to-five days are necessary to achieve full saturation with water at room temperature. The shear velocity is basically unaffected by water saturation, although it drops 2-3% as a result of the added inertia of the liquid. In comparison, in the most permeable rocks, the surface wave velocity drops as much as 40 % due to the presence of the slow surface mode. In low-permeability samples, below approximately 200 mD, the fluid is essentially immobilized in the pores by viscous forces. Such rocks behave like ordinary solids; the surface wave velocity is only a few percent lower than the shear velocity regardless whether the sample is saturated or not. Of course, both the velocity and the attenuation of the slow surface mode are sensitive to the dynamic permeability of the porous formation rather than to the static one. Consequently, quantitative assessment of the "static" permeability requires that the measurement be carried out at a sufficiently low frequency.

CONCLUSIONS

In conclusion, these experimental results provide clear evidence of the propagation of the new "slow" surface mode on the free surface of a fluid-saturated porous solid when the pores are closed at the surface by capillary forces. For ordinary solids, the surface wave velocity is always between 86% and 96% of the shear velocity. On the free surface of a

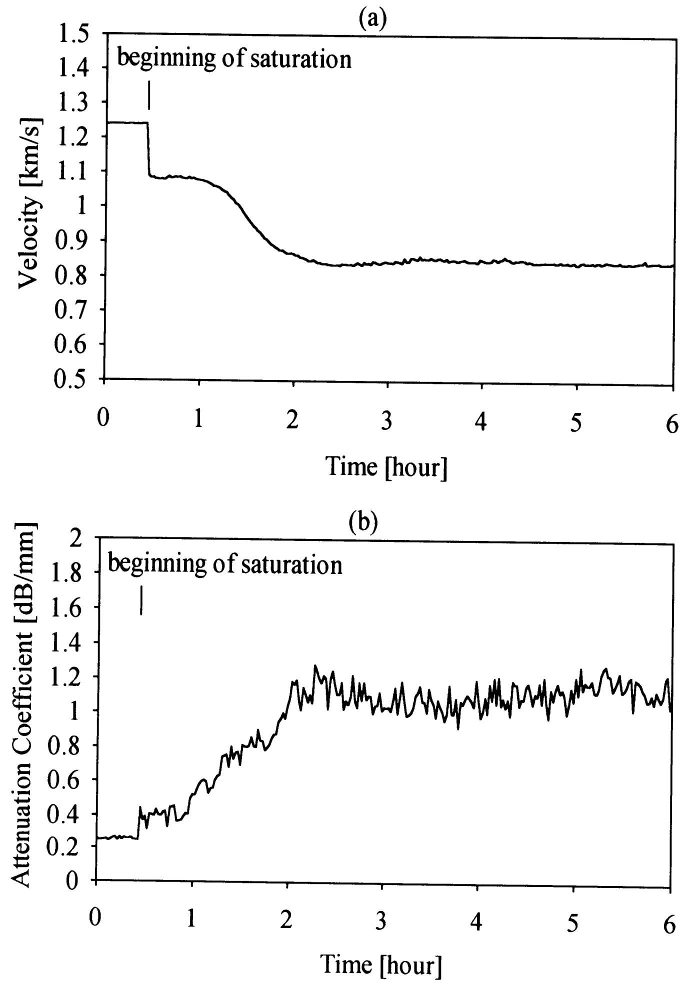

Fig. 4. Surface wave velocity (a) and attenuation coefficient (b) versus saturation time for methyl alcohol on a porous glass specimen at 100 KHz.

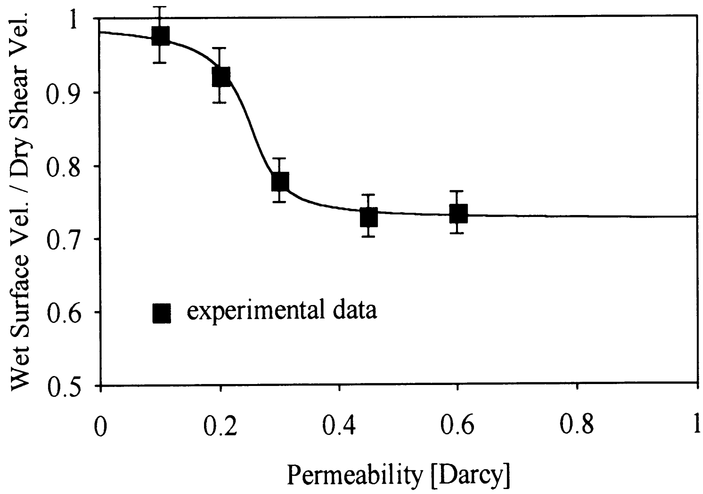

Fig. 5. Normalized surface wave velocity versus permeability in Massillon and Berea sandstones.

fluid-saturated porous solid, the "slow" surface wave velocity can be as low as 60% of the shear velocity. This phenomenon is a unique feature of permeable solids and can be exploited to assess the dynamic permeability of porous formations. Similar measurements conducted on water-saturated natural rocks indicate that the new surface mode can be observed in materials of 200 mD or higher permeability.

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